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Analysis of Radial Distribution Systems with FACTS Devices Using a Fast Line Flow-Based Algorithm

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Abstract

The electrical energy produced at the generating station is conveyed to the consumers through a network of transmission and distribution systems. It is often difficult to draw a line between the transmission and distribution systems of a large power system. It is impossible to distinguish the two merely by their voltage because what was considered as a high voltage because what was considered as a high voltage a few years ago is now considered as a low voltage. In general, distribution system is that part of power system which distributes power to the consumers for utilization. Analysis of radial distribution systems with embedded series FACTS devices is facilitated by a formulation of power flow equations with bus voltage magnitudes and line flows as independent variables The line flow-based (LFB) formulation is shown to provide easy implementation with multiple series FACTS devices in the system and enable direct evaluation of the FACTS device ratings.

Keywords: FACTS, LFB, Radial distribution system
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1. INTRODUCTION

All distribution of electrical energy is done by constant voltage system. In practice, the following distribution circuits are generally used.In this system, separate feeders radiate from a single substation and feed the distributors at one end only. Fig 1.1 shows a single line diagram of a radial system for d.c. distribution where a feeder OC supplies a distributor AB at point A. Obviously, the distributor is fed at one end only i.e., point A is this case. Fig 1.2 shows a single line diagram of radial system for a.c. distribution.

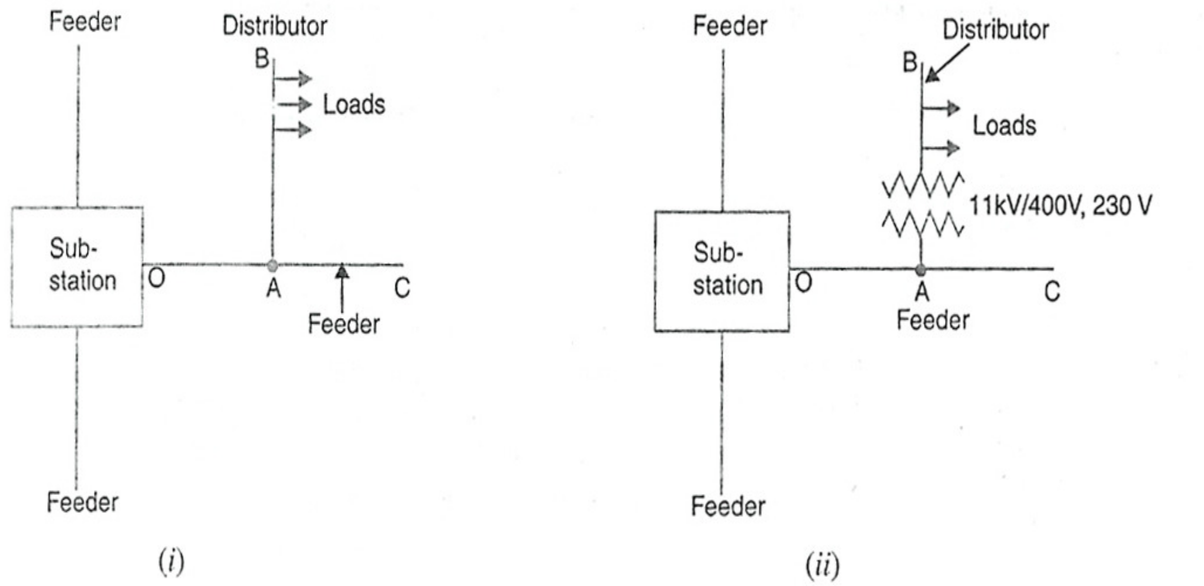

Fig: 1.1 Radial Systems

This is the simplest distribution circuit and has the lowest initial cost. However, it suffers from the following drawbacks:

The end of the distributor nearest to the feeding point will be heavily loaded.

The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are on the side of the fault away from the substation.

The consumers at the distant end of the distributor would be subject to serious voltage fluctuations when the load on the distributor changes. Due to these limitations, this system is used for short distances only.
1.2.2. Ring Main System
In this system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation. Fig 1.2 shows the single line diagram of ring main system for a.c distribution where substation supplies to the closed feeder LMNOPQRS. The distributors are tapped from different points M, O and Q of the feeder through distribution transformers.

The ring main system has the following advantages There are less voltage fluctuations at consumer's terminals. The system is very reliable as each distributor is fed via two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained. For example, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers via the feeder SRQPONM.

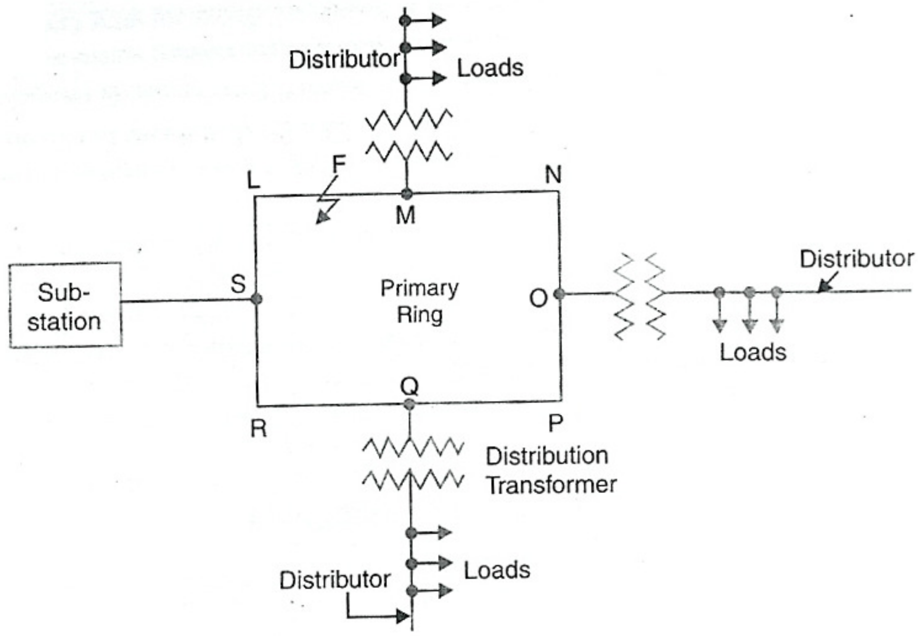

Fig 1.2 Ring main System

1.1. Distribution Load Flows
In this work main consideration is radial distribution system. Distribution power flow methods reported in the literature and actually implemented prefer to calculate line flows and voltage magnitudes using forward and reverse sweeps along a radial line. Mainly tree load flows are there.

1. LFB (Line Flow Based) algorithm
2. Decoupled LFB algorithm
3. Linear LFB algorithm

As stated in the introduction, there is a large incentive for the utilization of the power semiconductor technology in order to increase the network laudability. The faster response of the semiconductor-based controllers helps not only in handling dynamic problems but also in the steady-state problem of power-flow control. The main disadvantages of the mechanically switched controllers are the discrete control and the wear out of mechanical switches. The FACTS controllers provide smooth control with no (or few) mechanical parts and with high reliability.

FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded, lines. The possibility that current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with larger conductors, and use of one of the FACTS Controllers to enable corresponding power to flow through such lines under normal and contingency conditions. By providing added flexibility, FACTS Controllers can enable a line to carry power closer to its thermal rating. Mechanical switching needs to be supplemented by rapid-response power electronics. It must be emphasized that FACTS is an enabling technology, and not a one-on-one substitute for mechanical switches.

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2 LFB RADIAL DISTRIBUTION POWER FLOW MODEL

The nodal variables of bus voltage magnitudes and phase angles in the common power flow models do not reflect the ultimately required practical knowledge of the line flows. The power system operation focuses on maintaining a satisfactory level of voltage magnitudes, while dispersing real power and reactive power over transmission lines or feeders to the loads. Choice of line flows as variables will provide greater flexibility in problem resolution from a practical viewpoint.

The "line flow model" equations are derived using graph theory. In a power system structure, the line segments are called elements and their terminals are called nodes (buses). From graph-theory, concepts of trees and paths are used in developing the KCL and KVL equations through incidence matrices.

Real and reactive power balance equations at all busses except slack bus can be written using the incidence matrix. Since all shunt connections are excluded in the incidence matrix, their real and reactive power contributions are accounted for separately in the power balance equations. Real and reactive power loads, shunt capacitors and line charging susceptances can be treated as shunt branches. The real and reactive power mismatch equation of each bus except the slack bus is consider.

In this chapter, basic discussion is related to LFB, Decoupled LFB and linear LFB. Fig.2.1 shows IEEE 13 node test feeder system. This 13 bus system consist of 12 lines, 1 regulator, 1 transformer and 1 switch. In practice standard system contains 3phase unbalanced system data. This data is converted to 3phase balanced data or 1phase data. Positive sequence of 3phase unbalanced is nothing but a balanced domain and it simplifies the calculations.

The radial distribution system with thirteen nodes and twelve lines is shown Fig.2.1. Lines have only series impedances. The nodes are numbered arbitrarily. This typical distribution network graph is redrawn in Fig.2.2.with bus numbers in a perticular sequence starting from 1. Although bus-1 is given to the source bus here, the others encircled are arbitrary numbers as given in the original data list. This is useful when the network is reconfigured to meet the demand under different load and feeder scenarios. The flows in the branches are always oriented away from the source node, and so the direction arrows are ignored.

2.2. Radial Distribution Network

The radial distribution network graph has a tree structure with no loops as shown in Fig.2.2. The total number of lines equals the number of buses minus one. The pattern of incidence matrix depends on the order of lines and nodes, the incidence matrix of given distribution network is shown Fig.2.3. The Arbitrary order incidence matrix have a structure that depends on the order in which the lines are read from the data. Further, the incidence matrix is non square and singular. Any line oriented from a bus is given +1 and for towards node - 1 is assigned if the slack bus is excluded, the incidence matrix becomes square and non singular.

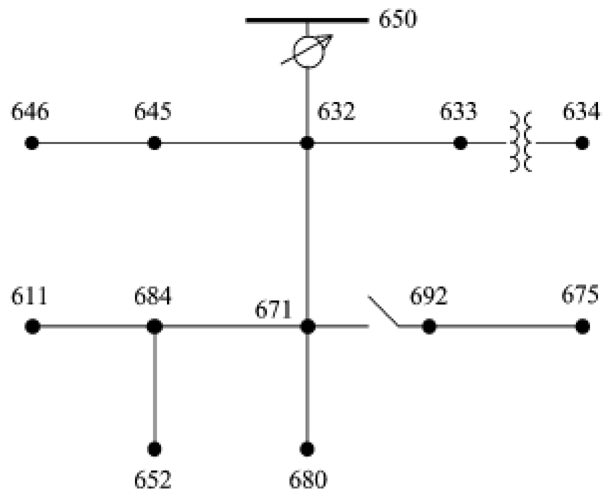

Fig.2.1 IEEE 13-node test feeder

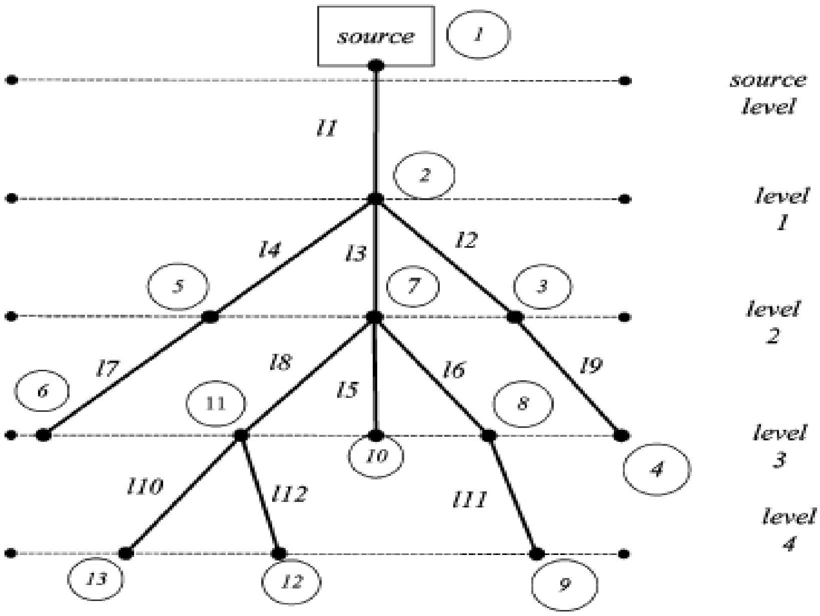

Fig.2.2: Graph of IEEE 13-node feeder

3 BFS (BREADTH FIRST SEARCH) METHOD

BFS is a web page searching method. BFS is a uniformed search method that aims to expand and examine all nodes of a graph systematically in search of a solution. In other words, it exhaustively searches the entire graph without considering the goal until it finds it. It does not use a heuristic.

The basic idea of BFS is to point out to as many buses as possible before penetrating deep into a tree. This means that we visit all the buses adjacent to the current level before going on to another one.

The brief description of BFS to renumber buses and branches may be summarized in the following three steps for building an optimal BFS tree.

1. Start at source bus as the first level and fan out to the "downstream" buses as the next levels.
2. On the same level, all bus numbers are ordered consecutively.
3. Branch renumbering is similar to that of the bus renumbering. At any level, a branch number is one less than the "upstream" bus number.

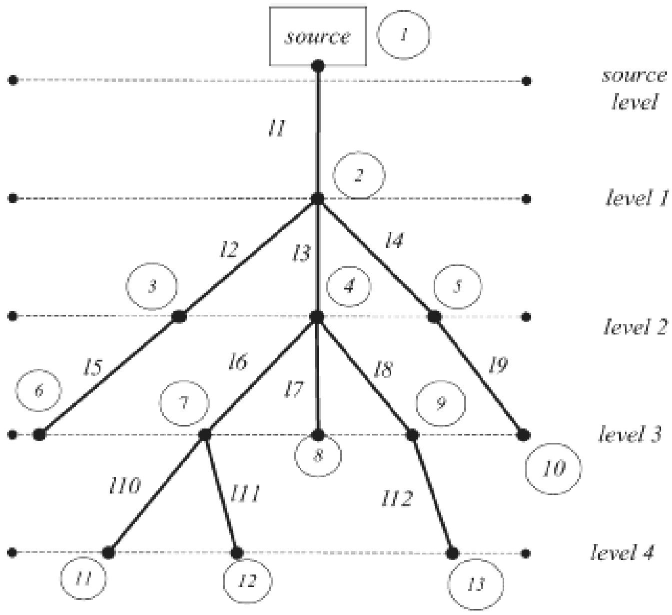

Fig.3.1: BFS numbering tree of the IEEE 13-node system.

$$A = \begin{array}{r} bus1 \\ bus2 \\ bus3 \\ bus4 \\ bus5 \\ bus6 \\ bus7 \\ bus8 \\ bus9 \\ bus10 \\ bus11 \\ bus12 \\ bus13 \end{array} \begin{bmatrix} 1 & & & & & & & & & & & \\ -1 & 1 & 1 & 1 & & & & & & & & \\ & -1 & & & 1 & & & & & & & \\ & & -1 & & & 1 & 1 & 1 & & & & \\ & & & -1 & & & & & 1 & & & \\ & & & & -1 & & & & & & & \\ & & & & & -1 & & 1 & & 1 & 1 & \\ & & & & & & -1 & & & & & \\ & & & & & & & -1 & & & & 1 \\ & & & & & & & & -1 & & & \\ & & & & & & & & & -1 & & \\ & & & & & & & & & & -1 & \\ & & & & & & & & & & & -1 \end{bmatrix}$$

Fig.3.2: Reorder Incidence Matrix for BFS optimal tree

An example of using the BFS algorithm is illustrated using the graph of IEEE 13 node feeder Fig.2.2, including the source node (at root, originally named as 650) called Bus 1, is shown in incidence matrix Fig.2.3. To conform to LFB load flow equations of the later section, the rows of the matrix are related to buses and its columns to branches. The BFS renumbering is applied to the 13-node test feeder. Before renumbering that test system is divided different sections. The renumbering is given according to the sections. The optimal BFS tree of the IEEE 13-node feeder is shown in Fig.3.1. Its reordered incidence matrix, including the source node, in shown in Fig.3.2. After the row corresponding to the source node is deleted, bus incidence matrix A becomes the upper triangle matrix in Fig.3.2. This sparse upper triangle incidence matrix results in reducing computational effort during the iterative process.

4. IEEE 34 BUS SYSTEM RESULTS

4.1 Decoupled LFB Method Results

Table 4.1.Line Data of load Pl and Ql at end buses of each line

LINE NO	LP	LQ	R	X	Pl	Ql
1	1	2	0.5473	0.4072	0	0
2	2	3	0.3669	0.273	0.0055	0.0029
3	3	4	6.835	5.086	0.0055	0.0029
4	4	5	1.0253	0.544	0.0016	0.0008
5	4	6	7.953	5.917	0.0016	0.0008
6	6	7	6.305	4.6913	0	0
7	7	8	0.0032	0.0016	0	0
8	8	9	0.0992	0.0494	0	0
9	9	10	0.302	0.1603	0.0005	0.0002
10	9	11	3.267	1.626	0.0034	0.0017
11	10	12	8.506	4.515	0.0049	0.0024
12	11	13	0.5352	0.2841	0.0169	0.0087
13	11	14	0.2688	0.1338	0.004	0.002
14	12	15	2.427	1.2883	0.0011	0.0005
15	14	16	6.5404	3.255	0.0135	0.007
16	16	17	0.1664	0.0828	0.0067	0.0033
17	17	18	4.1213	2.1874	0.0004	0.0002
18	17	19	11.785	5.865	0.0004	0.0002
19	19	20	0.0032	0.0016	0	0
20	20	21	1.5679	0.7802	0.0015	0.0007
21	20	22	0	0	0.0049	0.0025
22	21	23	0.2862	0.152	0	0
23	21	24	1.8655	0.9283	0.0032	0.0017
24	22	25	2.24	1.666	0.0178	0.009
25	24	26	0.6464	0.3217	0.09	0.045

LINE NO	LP	LQ	R	X	Pl	Ql
26	24	27	0.0896	0.0446	0.0348	0.0212
27	26	28	0.8576	0.427	0.0009	0.0005
28	27	29	0.432	0.215	0.0122	0.0063
29	28	30	0.2752	0.1369	0.0864	0.1258
30	28	31	0.0896	0.0446	0.0094	0.0062
31	29	32	1.165	0.5796	0.0028	0.0014
32	31	33	0.5894	0.436	0.0068	0.0034
33	32	34	0.1696	0.0844	0.0028	0.0014

Table 4.2.Real &Reactive Power at each Bus

BUS NO	Peff	Qeff
1	0.3538	0.3594
2	0.3538	0.3594
3	0.3483	0.3565
4	0.3428	0.3536
5	0.0016	0.0008
6	0.3396	0.352
7	0.3396	0.352
8	0.3396	0.352
9	0.3396	0.352
10	0.0338	0.0174
11	0.3053	0.3344
12	0.0304	0.0157
13	0.004	0.002
14	0.2964	0.33
15	0.0135	0.007
16	0.2953	0.3295
17	0.2886	0.3262
18	0.0004	0.0002
19	0.2878	0.3258
20	0.2878	0.3258
21	0.1963	0.2801
22	0.09	0.045
23	0.0032	0.0017
24	0.1882	0.2759
25	0.09	0.045
26	0.062	0.0365
27	0.1084	0.2304
28	0.0272	0.0153
29	0.1075	0.2299
30	0.0094	0.0062
31	0.0056	0.0028
32	0.0211	0.1041
33	0.0028	0.0014
34	0.0143	0.1007

28	0.9365	2.7018
29	0.9364	2.7248
30	0.9365	2.7019
31	0.9365	2.7018
32	0.936	2.7536
33	0.9365	2.7017
34	0.936	2.7577

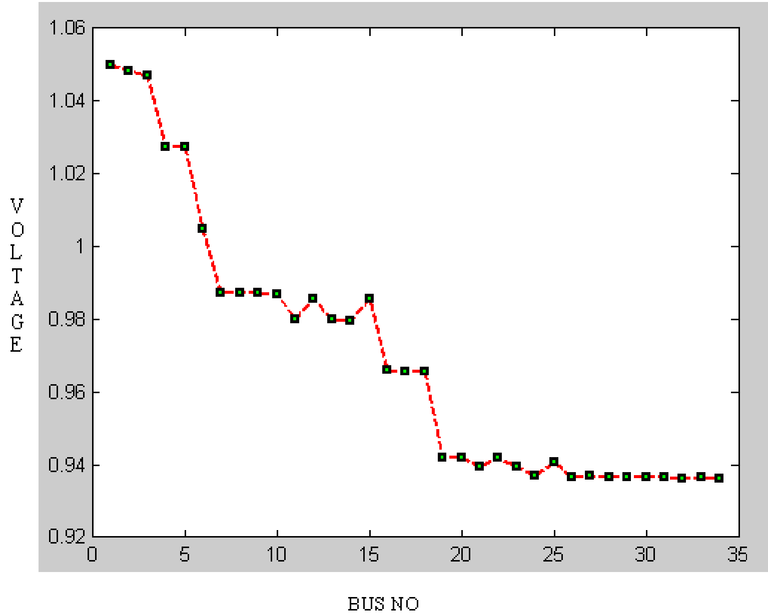

Fig 4.1.Graph: Busno *V*s Voltage

LFB and D-LFB methods have converged in 4 iterations for 13 and 34 bus systems. The linear LFB has taken only two iterations but the results are not accurate enough.

Table 4.3. Comparison of solution times, in seconds.

IEEE Distribution systems	LFB	D-LFB	Linear LFB
IEEE 13-node	0.03	0.02	0.01
IEEE 34-node	0.04	0.03	0.02

It may be noted that with good accuracy and reduced time the D-LFB establishes its superiority other two methods (LFB and linear-LFB).

CONCLUSIONS

In this thesis three algorithm for line flow study of radial distribution system have been considered. Three algorithms Line Flow Based (LFB), Decoupled LFB, Linear LFB formulation and Decoupled LFB with embedded series FACTS devices (TCSC and TCVR) are implemented in this thesis and tested on IEEE 13- bus and IEEE 34-bus systems.

Breadth first search method is used for network modification .The incidence matrix was converted to upper triangular matrix. This method incorporated with LFB, it is termed Decoupled LFB. In this method, commutation time is low compared to LFB.

By neglecting losses in the formation of LFB method a new method called linear LFB was developed.

The three algorithms LFB, Decoupled LFB, Linear LFB are implemented on IEEE 13 bus and IEEE 34 bus distribution systems and observed that Decoupled LFB is taking less time and produced accurate results compared other two algorithms. Among three methods the Decoupled LFB is the best one. Thus, in this thesis Decoupled LFB embedded with series FACTS devices is implemented and developed a software package. Variable swapping method is incorporated in the Decoupled LFB for the system with TCSC or TCVR.

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